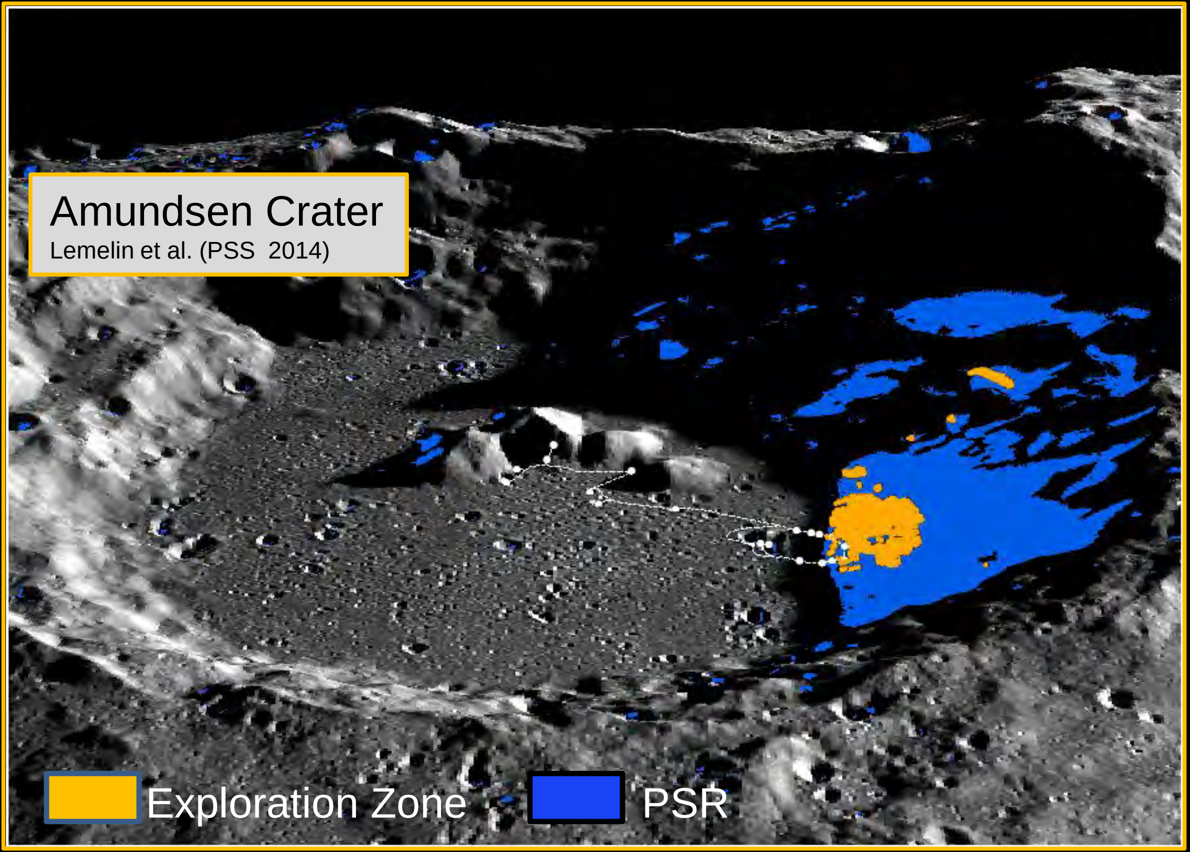
Regolith properties of permanently shadowed regions (PSRs) in polar regions of the Moon and implications for rover trafficability: Outlining the problem



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Polar Regolith Workshop

NASA SSERVI
3 December 2015

LUNAR AND PLANETARY INSTITUTE

Regolith and Underlying Structure

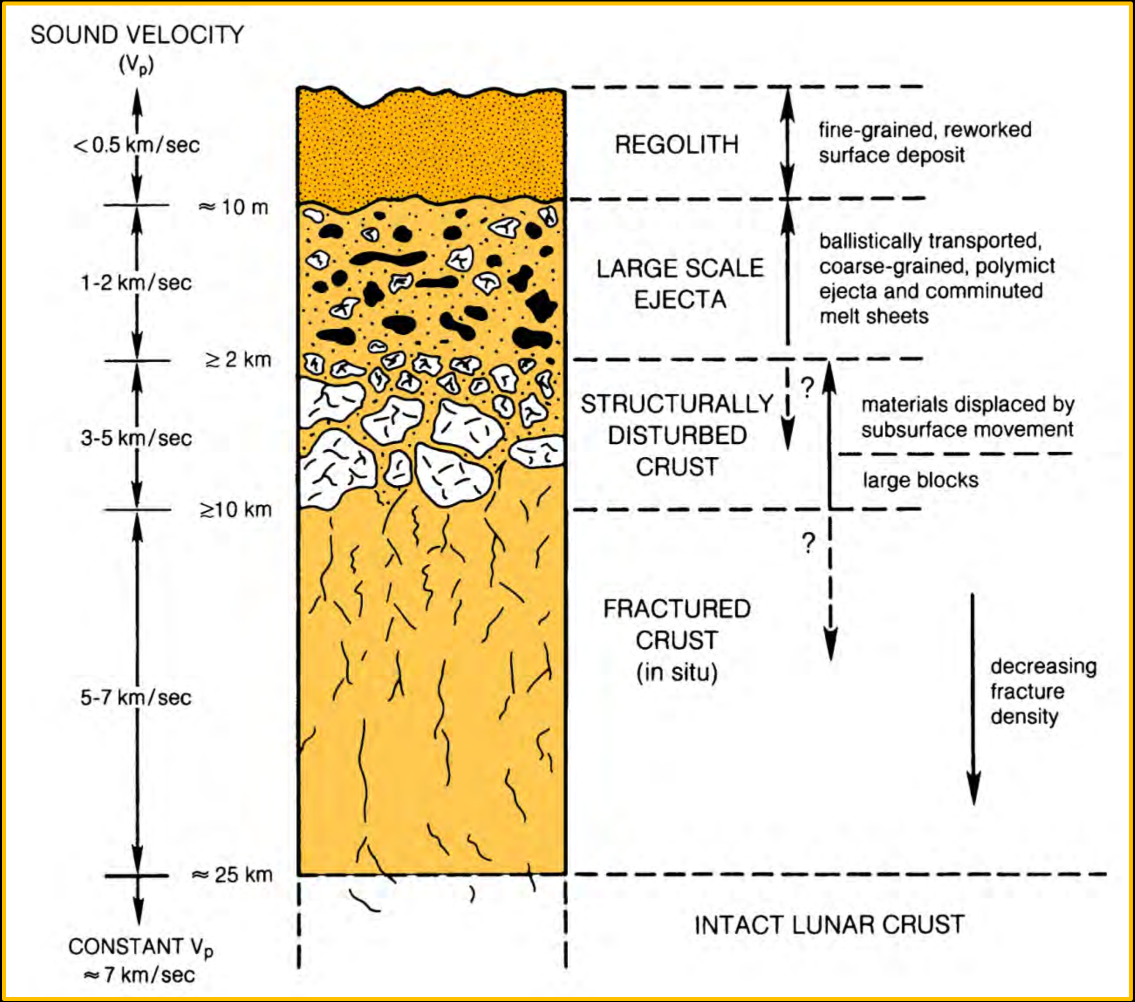


Illustration credit: Friedrich Hörz (NASA JSC)

Lunar Regolith

The regolith is the uppermost layer in a sequence of units affected by over 4 billion years of impact cratering processes.

In general, the regolith is a unit a few meters thick.

Components of Lunar Regolith

- Regolith
  - Layer or mantle of fragmental and unconsolidated rock material, whether residual or transported, that nearly everywhere forms the surface of land and overlies or covers bedrock (Bates & James, 1980)
  - ~10 m thick in the lunar highlands, where it overlies a mega-regolith that is crudely estimated to be 1 to 3 km thick

- Lunar soil
  - Sub-centimeter fraction of (unconsolidated) regolith
  - Rate of accumulation
    - Avg = 1.5 mm/Myr (or 1.5 millimeters per million years)
    - Soil formation was particularly high during 3.8-4.0 Ga bombardment; ~1 order of magnitude higher than in younger regolith

In contrast -------

- Regolith breccias
  - Polymict breccias are consolidated rocks that contain rock, mineral, and glass fragments in a glassy matrix (agglutinates).

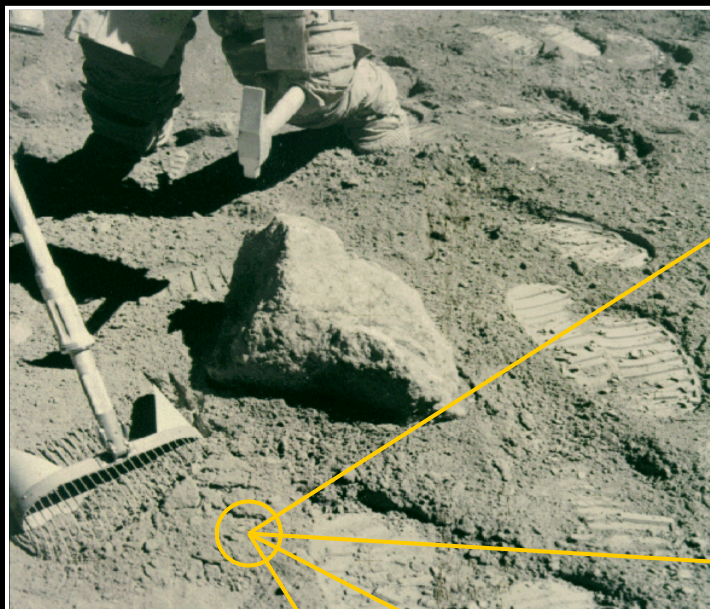
Lunar Soil


Detail of AS11-40-5877

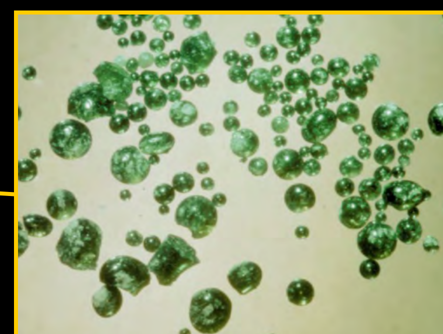

Detail of AS16-116-18689

- Sub-centimeter fraction of regolith
- Mixed with rock fragments
- Porosity of soil is often ~50%
- On top of denser (packed) regolith

Lunar Soil Components

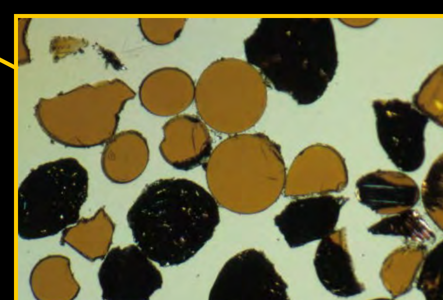


Anorthosite (An)
Basalt (Ba)
Breccia (Br)
Glass Spherule (Gl)



Green glass spherules or vitrophyres

Agglutinates



Orange glass spherules or vitrophyres

Regolith Processes

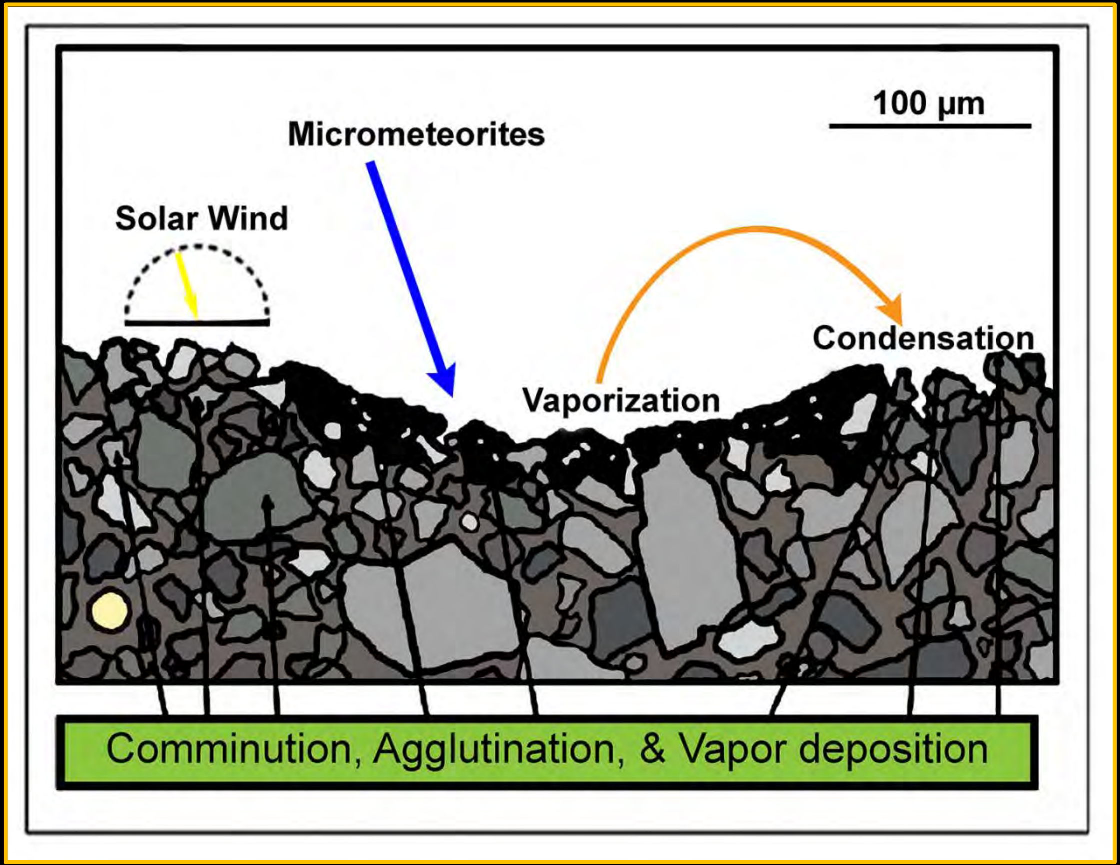


Illustration courtesy of Larry Taylor

Regolith

Produced on an airless body

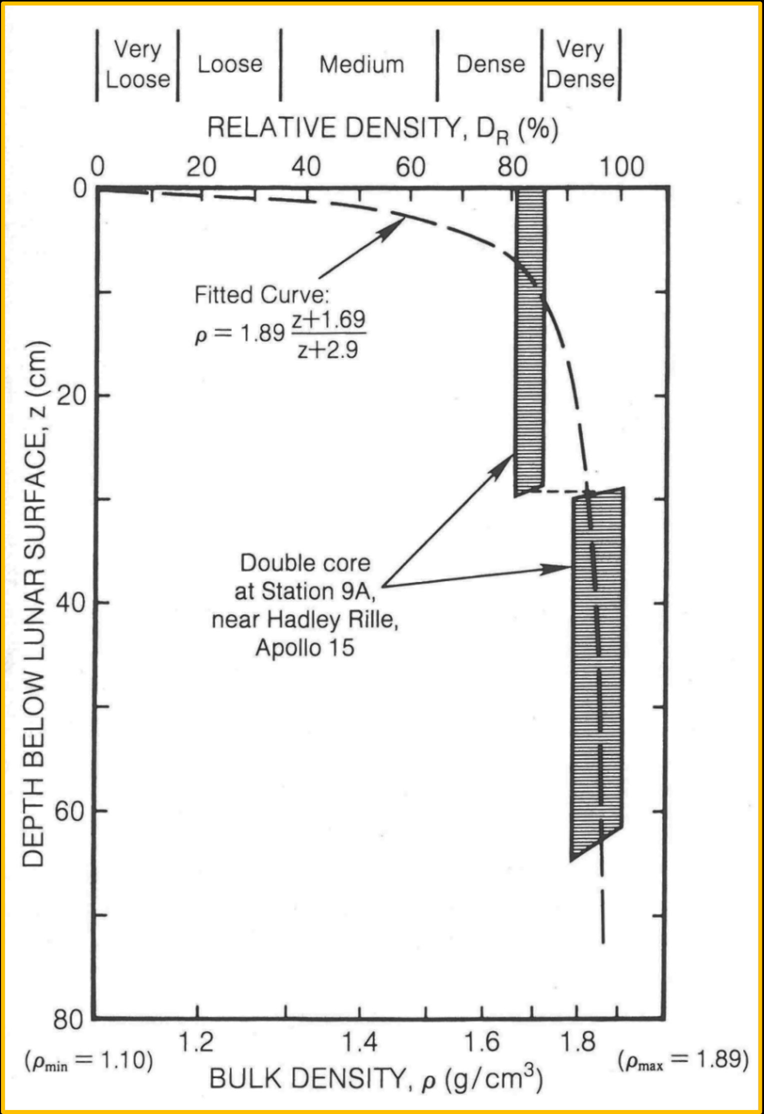
Commonly affected by micrometeoritic impact at speeds >10 km/s

- Comminuting soil
- Yet, also producing agglutinates
- With cycles of vaporization and condensation

Solar wind bombardment

- Producing fission tracks
- Implanting solar wind gases (^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, ^{132}Xe)

Soil Densities – Apollo 15 data



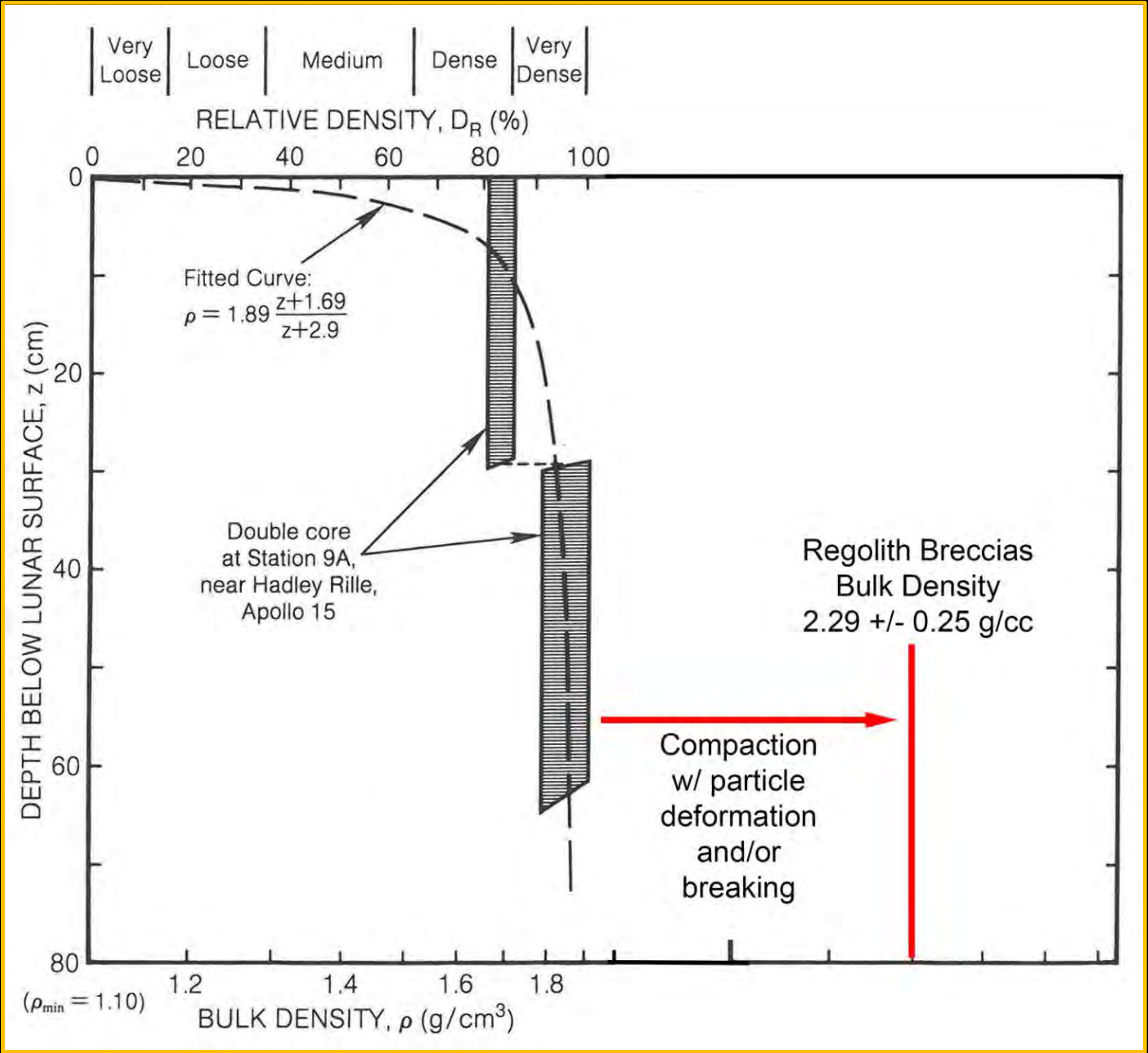
Bulk & Relative Densities

As the relative density approaches 100% with depth in Apollo 15 lunar soil, the bulk density approaches 1.9 g/cc.

The soil is very loose in the upper 10 cm, but rapidly becomes dense to very dense below 20 cm.

Carrier et al. (1991)

Soil Densities & Regolith Breccia Densities – Apollo 11, 15, & 16 data



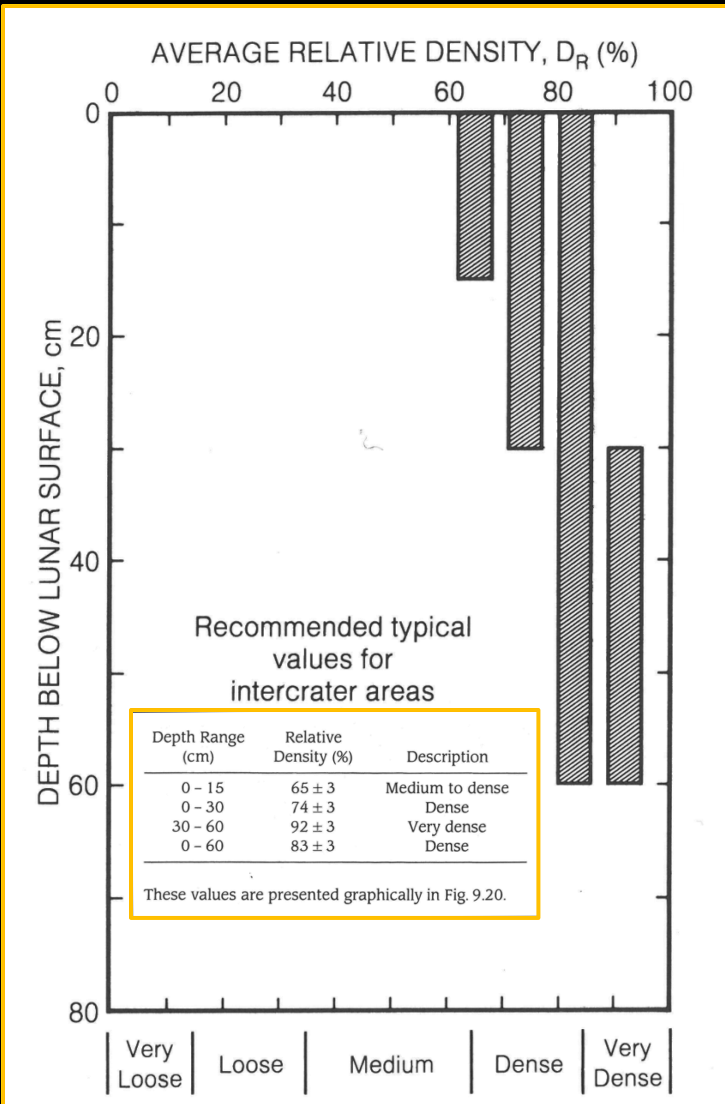
Bulk & Relative Densities

Compaction of a soil will produce a regolith breccia with a bulk density of ~2.3 g/cc based on analyses of twenty-six Apollo 11, 15, and 16 samples.

Compaction or shock-lithification of lunar soil can be produced by impact events.

Modified after Carrier et al. (1991)

Soil Densities – Recommended values based on all Apollo missions



Depth Range (cm)	Relative Density (%)	Description
0 – 15	65 ± 3	Medium to dense
0 – 30	74 ± 3	Dense
30 – 60	92 ± 3	Very dense
0 – 60	83 ± 3	Dense

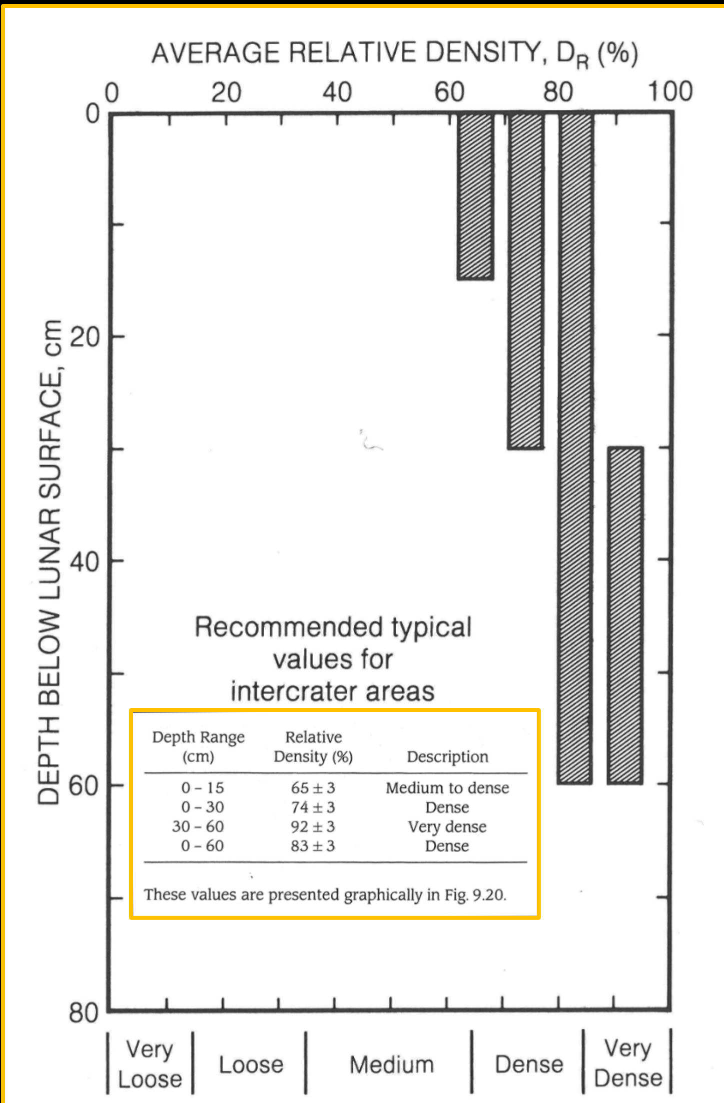
These values are presented graphically in Fig. 9.20.

Relative Density

The relative density reflects the reduction of porosity by enhanced particle packing (i.e., the increase in density that can occur without particle deformation and breakage).

Carrier et al. (1991) after Mitchell et al. (1974) and Houston et al. (1974)

Soil Densities – Recommended values based on all Apollo missions



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These values are presented graphically in Fig. 9.20.

Relative Density

Relative density of lunar soil is ~65% in upper 15 cm

Relative density increases to >90% below depths of 30 cm

Values are much higher than the 65-75% limit obtained in soils at terrestrial construction sites

Implies lunar soils were not emplaced by some type of sifting mechanism, but were instead extensively shaken and densified, probably as a consequence of repeated impact events.

e.g., Carrier et al. (1991)

Regolith Processes - Impact Cratering

AS15-97-13177

Pervasive Impact Cratering

Locally, impact cratering can

- Vaporize material &
- Melt material.

Largest volume of material is, however,

- Brecciated (forming lower density material) or
- Compressed (forming higher density material).

Beyond the site of impact, cratering also

- Generates seismic shaking

Regolith Processes - Impact Cratering

AS15-97-13177

Pervasive Impact Cratering

Seismic shaking has significant effects because

- Seismic shaking is not damped very fast on the Moon (hence the phrase, the Moon rings like a bell), so it effects regolith for a relatively long period of time after each event
- For example, a meteoroid impact on April 8, 1970, which is an instantaneous event, nonetheless generate seismic vibrations that persisted for an hour.
- Impact shaking has a cumulative effect over geologic time and
- Involves a very large number of impact events.

Regolith Processes - Impact Cratering

AS15-97-13177

Pervasive Impact Cratering

For example, within the area equal to that of a 1-km diameter crater (e.g., about the size of North Ray Crater at the Apollo 16 landing site or Meteor Crater in Arizona), there are

- >10 thousand 10-m-diameter craters
- >10 million 1-m-diameter craters

Per a cumulative crater frequency report by Hörz et al. (1991)

Impact cratering is a global process, so the seismic energy affecting Apollo sites is similar to that in polar regions, with only a few caveats.

Could Regolith Properties Differ in Permanently Shadowed Regions?

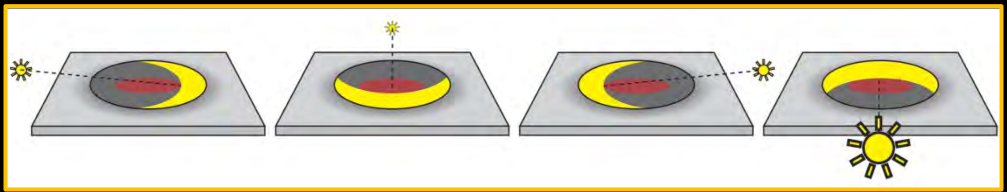
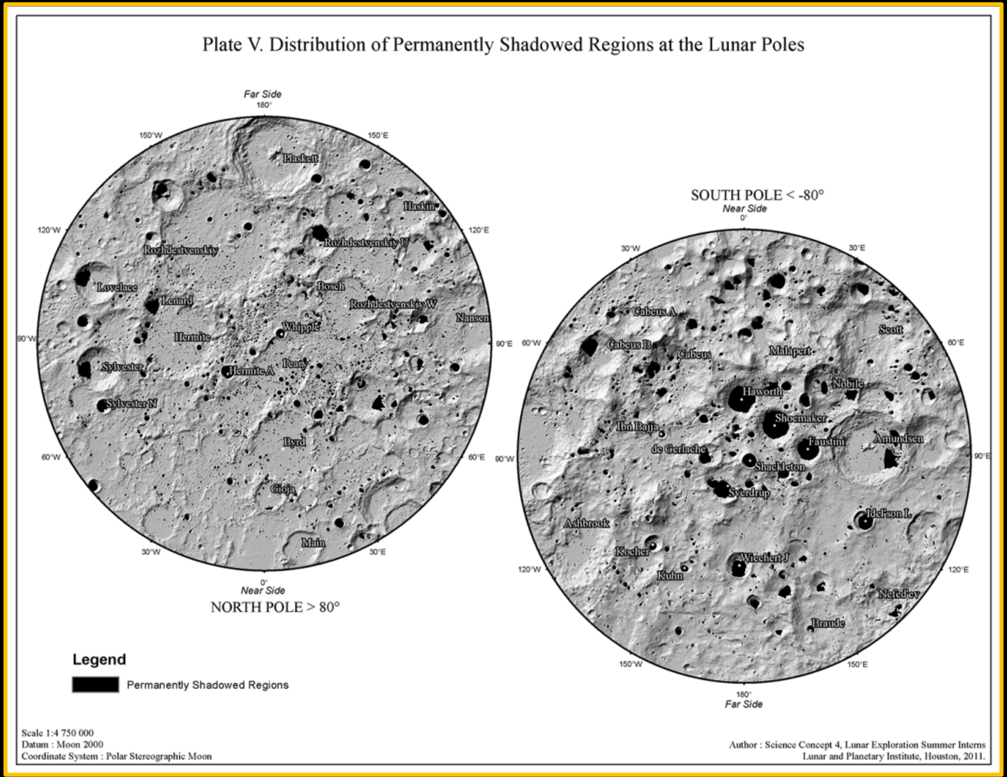


Illustration credit: LPI



Lack of Sunlight

The permanently shadowed regions of the Moon lack direct sunlight.

Could lack of sunlight or daily thermal cycling affect regolith properties?

Fortunately, we have *in situ* data regarding the effects of permanent shadow.

Samples from Permanently Shadowed Locations

Charlie Duke photographs John Young at Station 13's Shadow Rock. Duke sampled the regolith at the deepest point of the shadow by getting on his knees.

We have sampled PSRs before

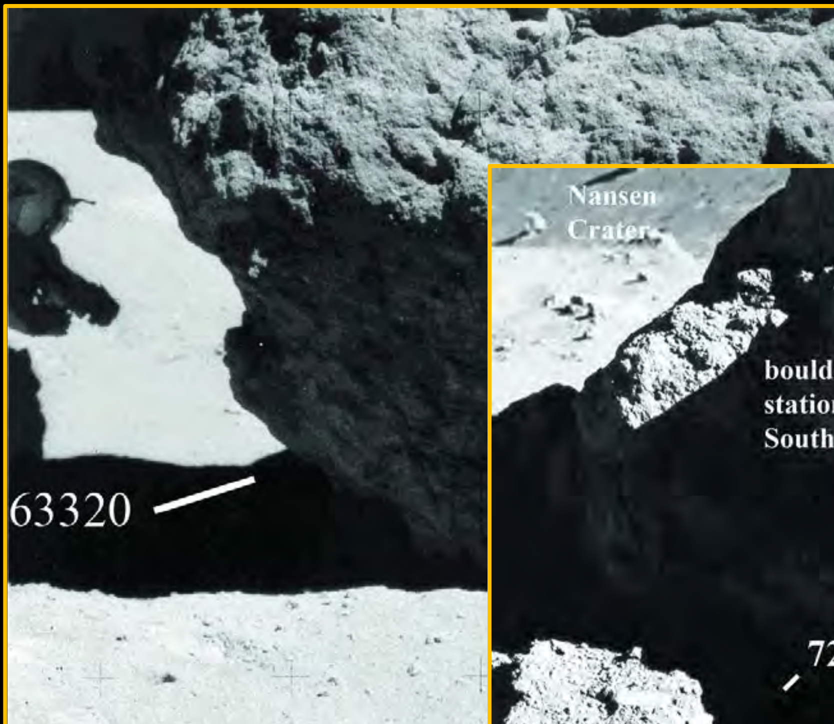
Small PSRs were identified at the Apollo landing sites.

Astronauts were unaffected when they approached and entered the PSRs

Here – at the Apollo 16 landing site – an astronaut steps into a shadowed location.

No physical differences in these shadowed soils were noted by astronauts

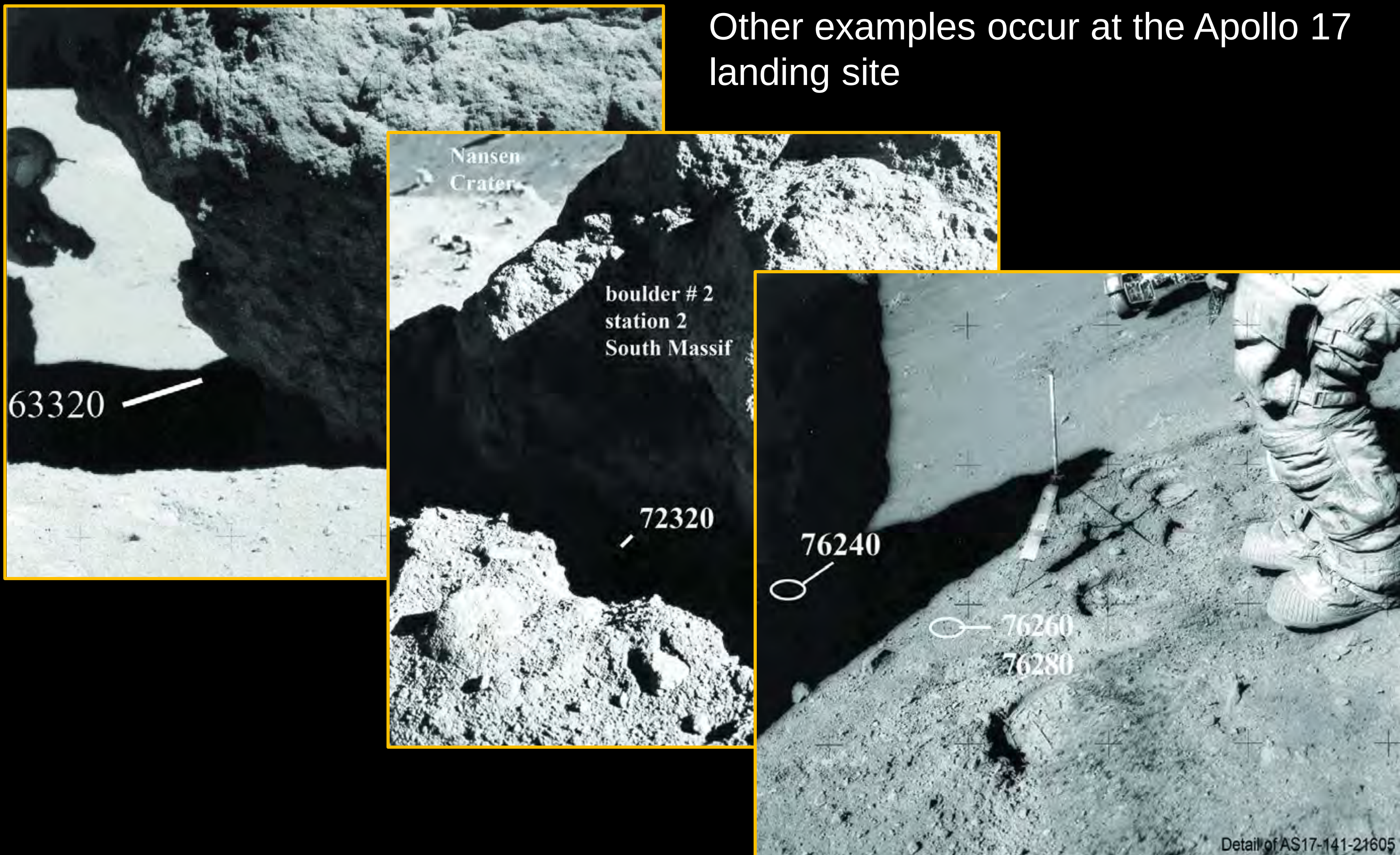
Samples from Permanently Shadowed Locations



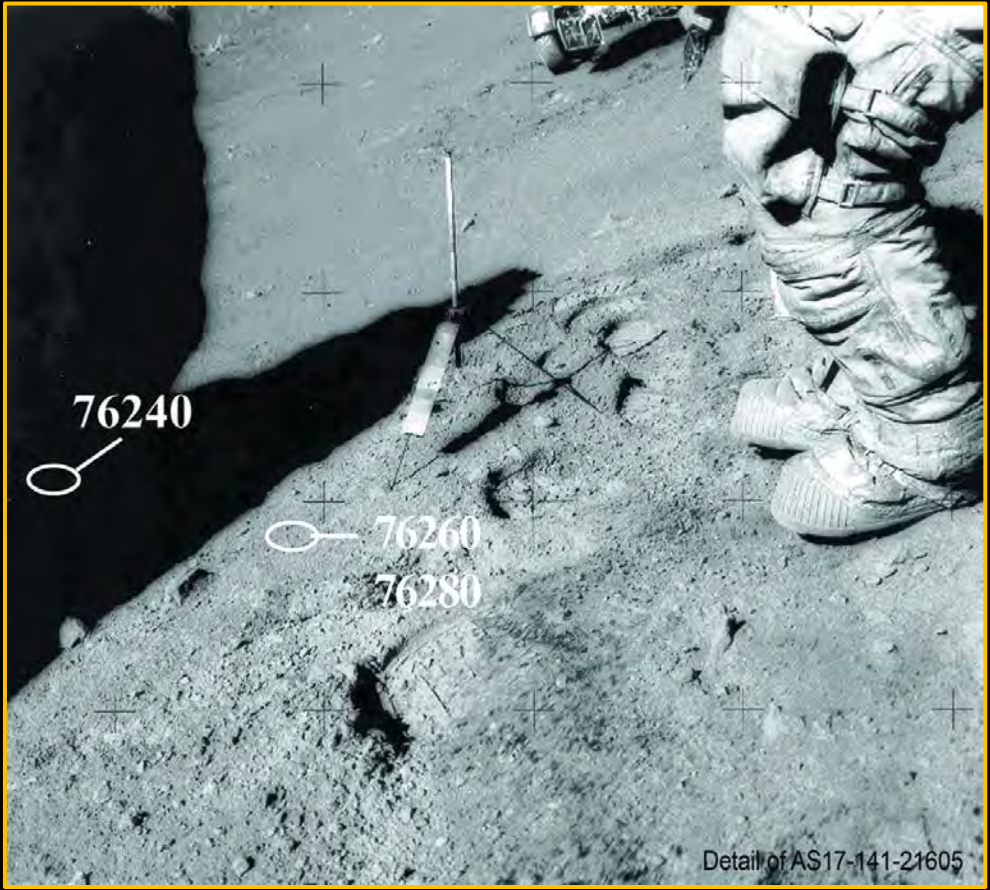
Other examples occur at the Apollo 17 landing site

Samples from Permanently Shadowed Locations

Other examples occur at the Apollo 17 landing site



Samples from Permanently Shadowed Locations



We have sampled PSRs before

These shadowed locations have been shadowed for significant geologic time.

e.g., at the location of 76240, the boulder and shadow have existed in this configuration for 22 million years

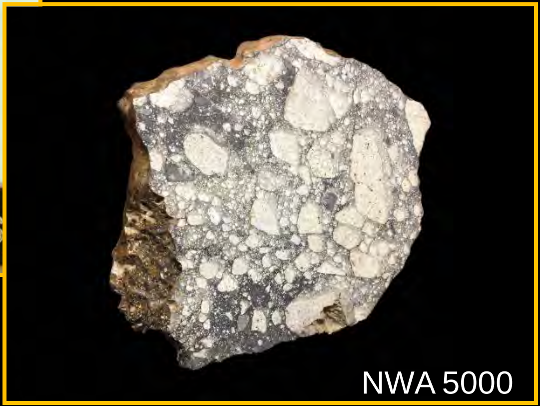
A small addition to the shadowed soil was produced 65 thousand years ago by a nearby impact

Laboratory measurements detected enhanced volatile abundances

Samples from Polar Regions - Lunar Meteorites

MAC 88105

Y 791197



NWA 5000

Global Sampling

Lunar meteorites are launched from all regions of the Moon

No anomalous regolith particles or particle size-distributions are seen among lunar meteorites, some of which likely come from polar regions.

Caveat – if PSR soil regolith does not form coherent regolith breccias, they may not survive launch and delivery to Earth.

Could Regolith Properties Differ in Permanently Shadowed Regions?

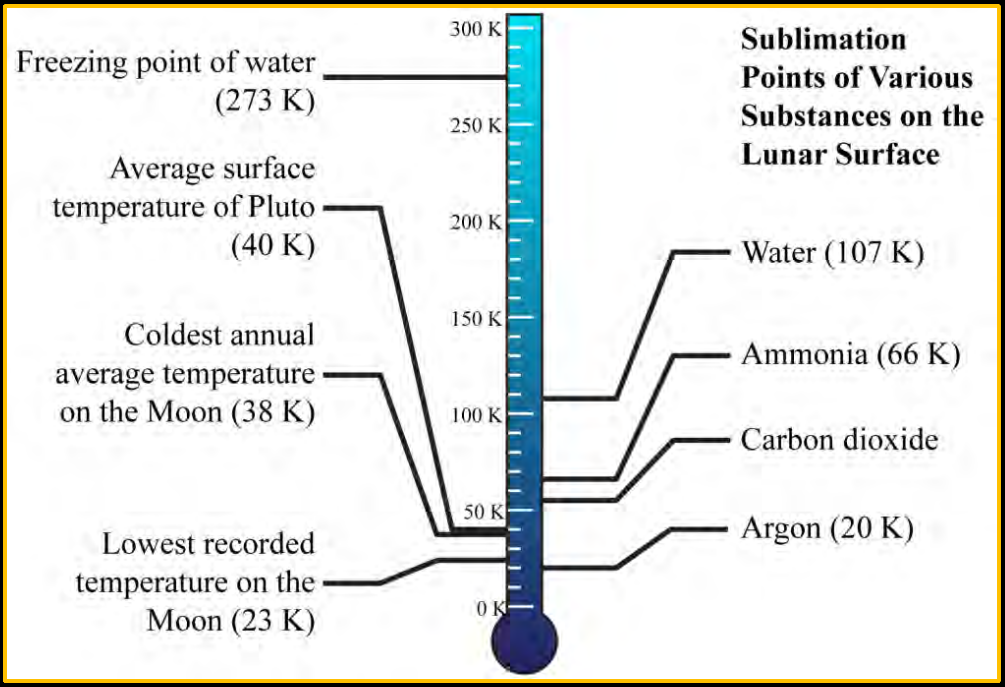


Illustration credit: LPI

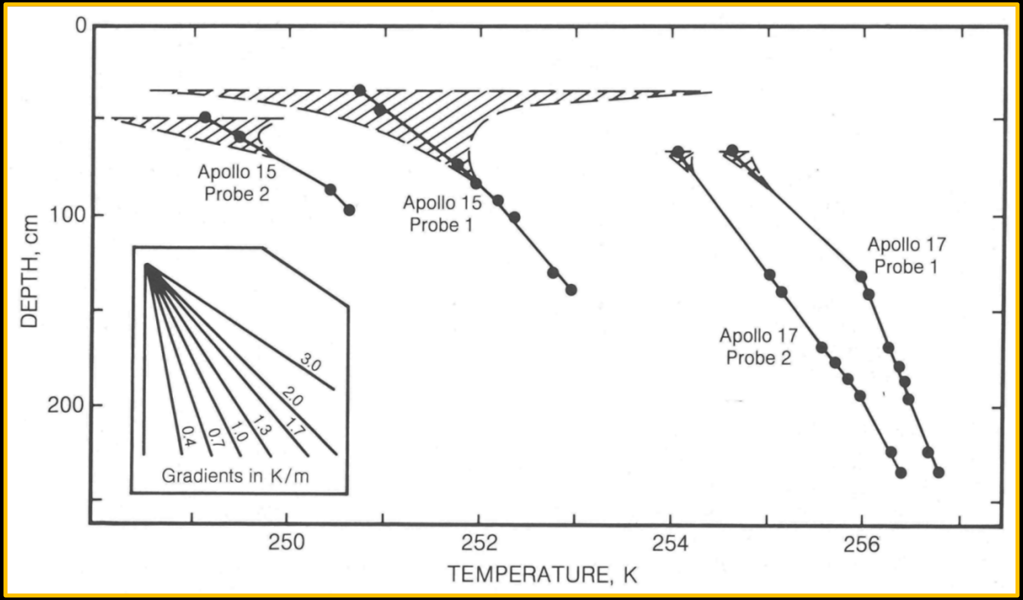
Cold Temperatures

The permanently shadowed regions of the Moon lack direct sunlight.

That, in turn, can lead to cold temperatures.

Although we do not have *in situ* data about the effects of cold sub-100 K temperatures, some insights can be gleaned from *in situ* measurements of thermal gradients as a function of depth in the regolith.

Could Regolith Properties Differ in Permanently Shadowed Regions?



Carrier et al. (1991), after Langseth & Keihm (1977)

Cold Temperatures

In the diagram to the left, the hatched areas reflect measured day-night fluctuations in temperature, which were <6 K in the upper 30 to 70 cm.

Below ~50 cm, there is no significant day-night temperature cycling (& steady temperature gradients are controlled by internal heat flow).

That suggests any physical effect caused by a lack of daily heating in a PSR would be limited to the upper 50 cm.

Could Regolith Properties Differ in Permanently Shadowed Regions?

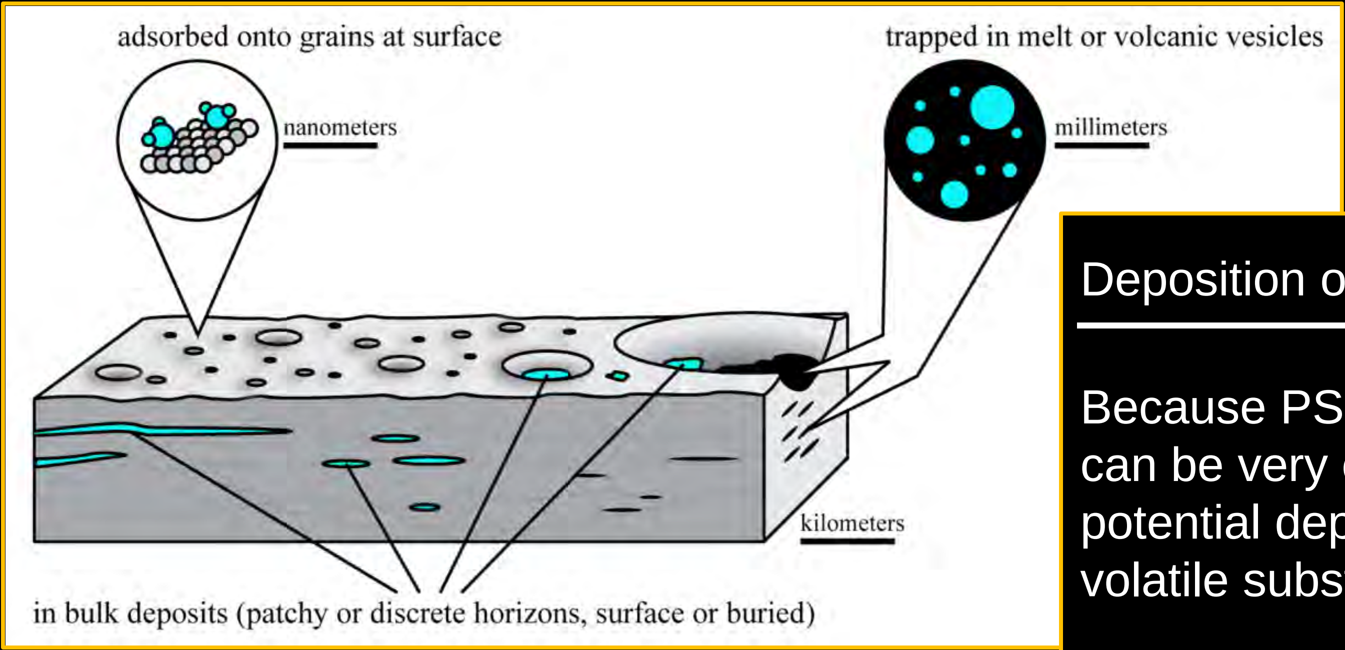


Illustration credit: LPI

Deposition of Ice

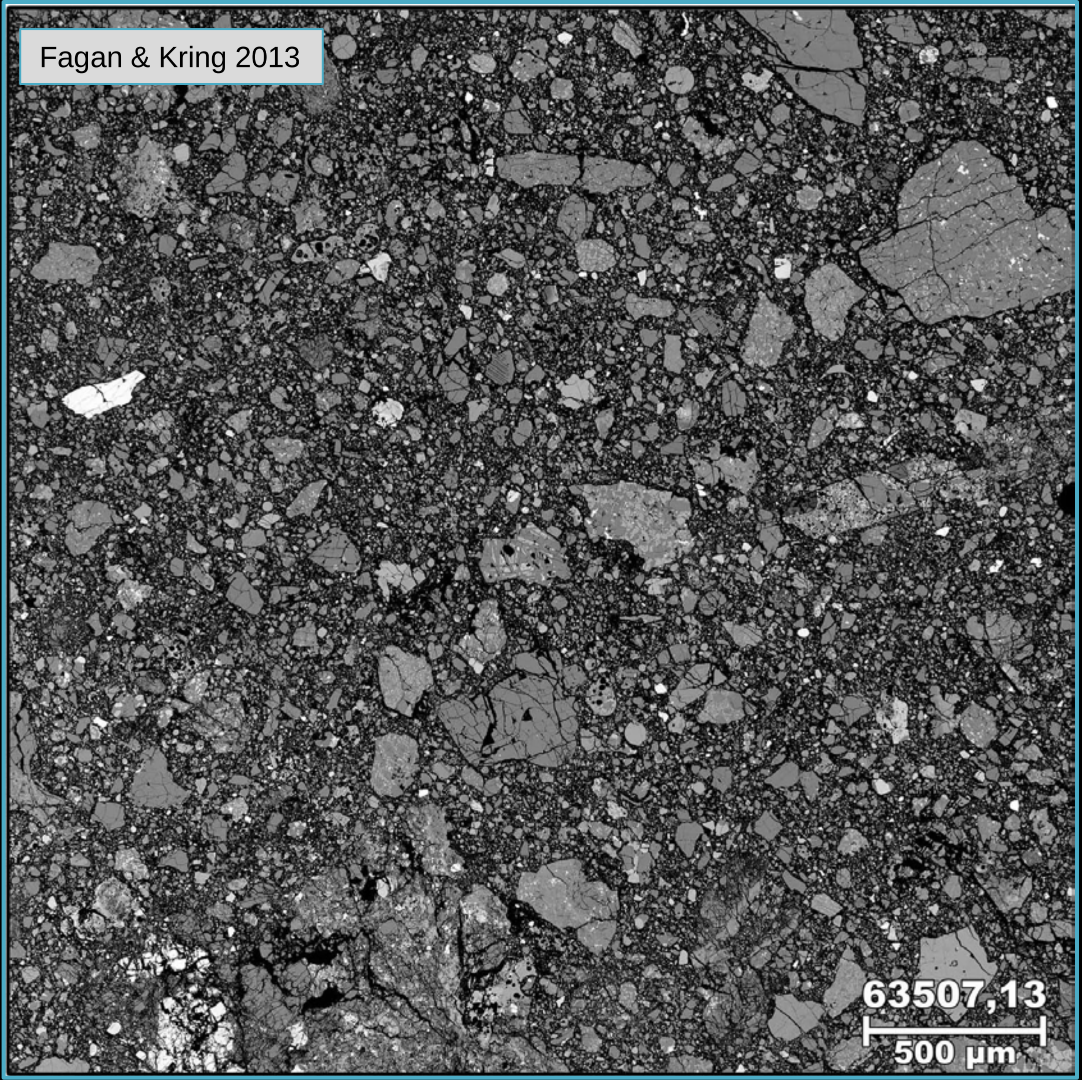
Because PSRs lack sunlight and can be very cold, they are potential depositional sites for volatile substances like water ice.

Icy materials can be deposited in the regolith in several (as yet untested) forms, as illustrated on the left.

What effect might that have on trafficability?

Hypothetical Deposition of Ice

Fagan & Kring 2013



Highland regolith breccia

Sample 63507 is representative of highland regolith breccias

Feldspathic

Submature

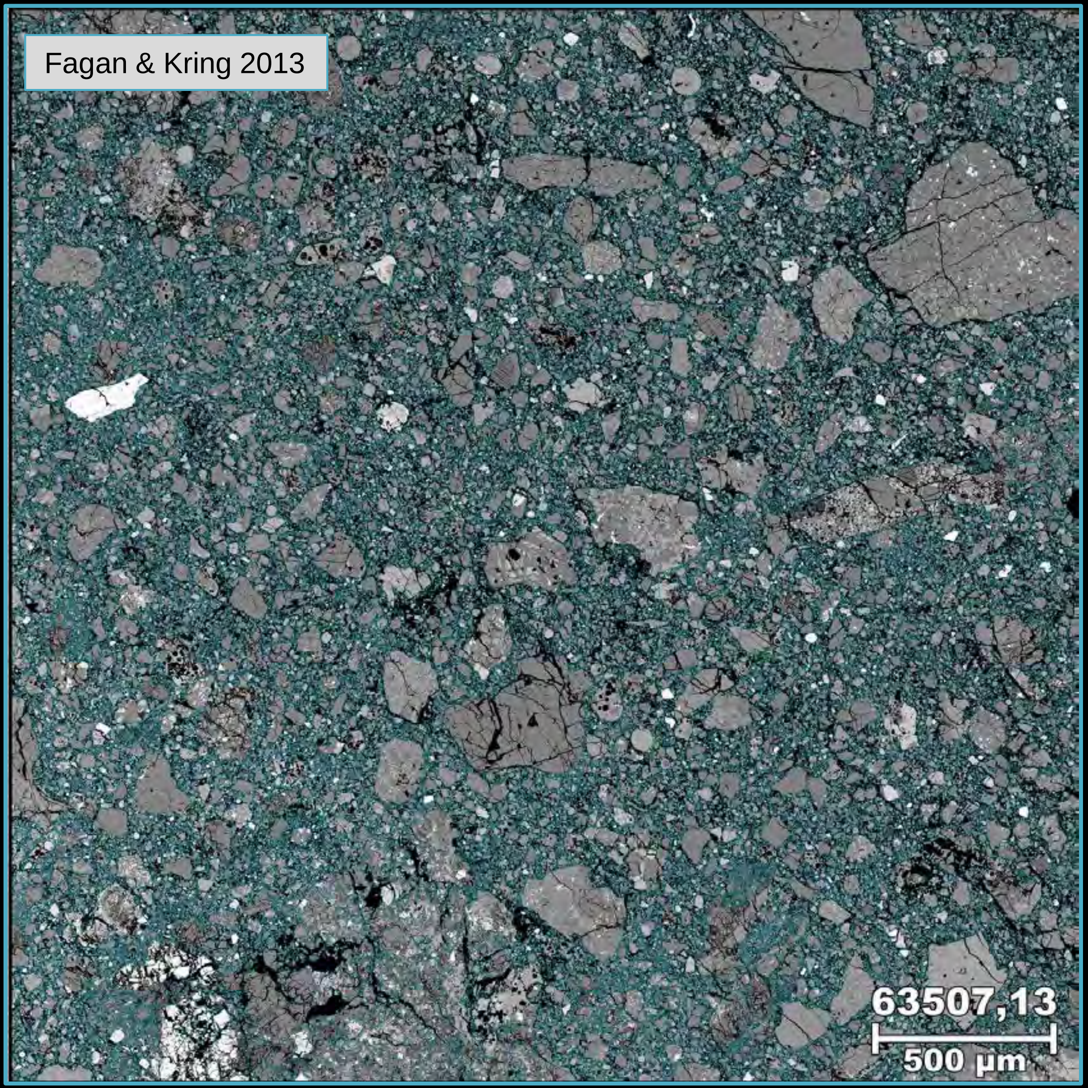
Friable

Estimated porosity: 30%

Estimated bulk density: 2 g/cm^3

Field of view = 3 mm

Hypothetical Deposition of Ice



Water in regolith

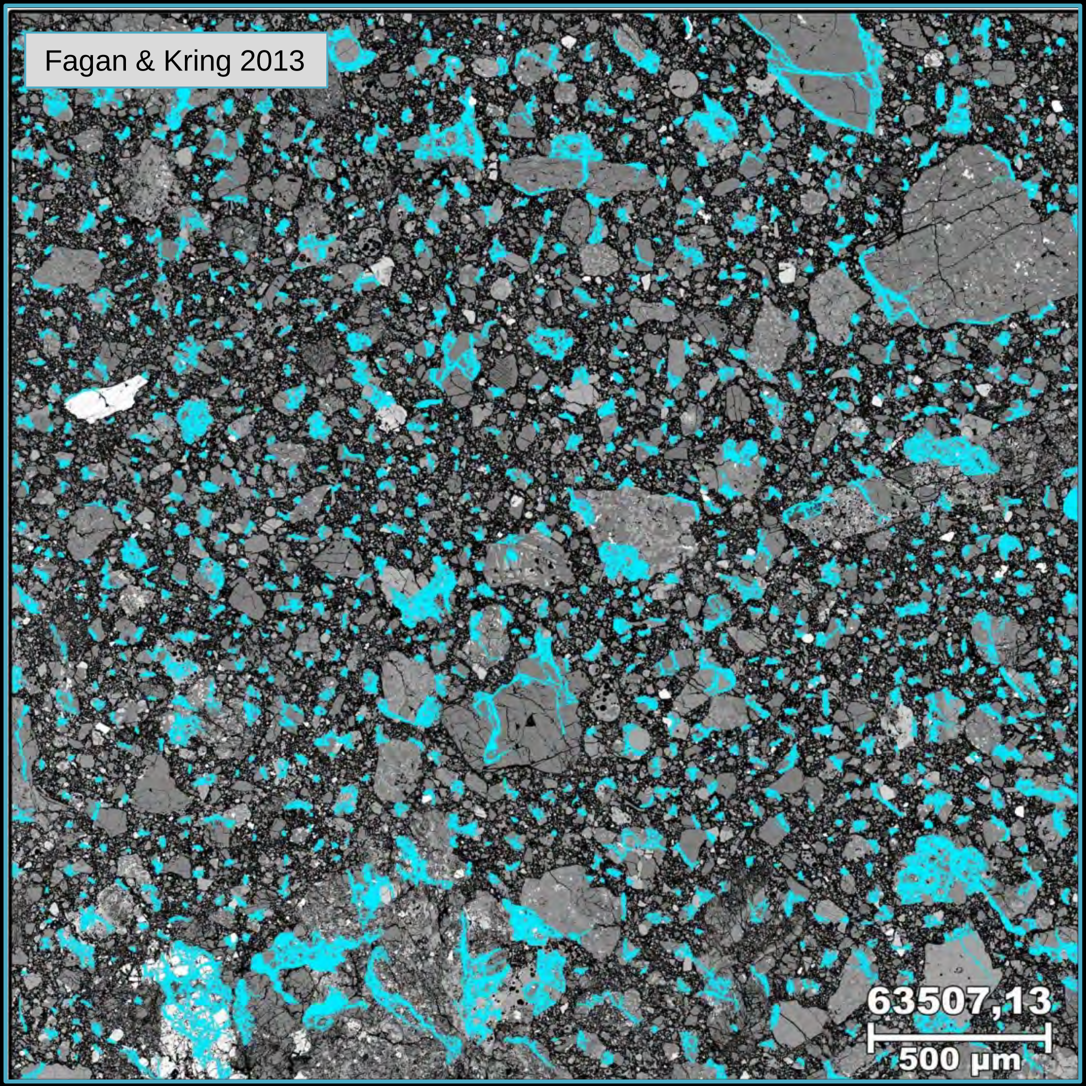
Estimates for mass of water in the regolith hit by the LCROSS impactor are ~5 wt% (e.g., Colaprete et al., 2010)

This is ~10 vol% of a highland regolith breccia, because of the density contrast between water and the rocky breccia.

If the water ice was distributed along grain boundaries, it would look like the image to the left.

Field of view = 3 mm

Hypothetical Deposition of Ice



Water in regolith

If that water ice, instead, filled large pore spaces in the regolith, it could look like the image to the left.

In either case, the result is a lower porosity and better cemented material.

Thus, the addition of water ice in a regolith breccia would seem to enhance cohesion and bearing capacity, properties that would enhance trafficabiilty

Field of view = 3 mm

Could Regolith Properties Differ in PSRs?

Why are we here?

Despite lunar surface experience gained through the Apollo and Luna programs, including the success of both a robotic and human-rated rover, uncertainties about regolith properties in PSRs remain.

In particular, hints of unusually high porosity soil and/or regolith have emerged from a new generation of orbiting instruments and the LCROSS impact experiment.

Today's goal is to review that new data and any relevant modeling to better constrain the parameters that will govern the design of future mobility systems, such as the Resource Prospector rover. For example,

- Is the regolith in PSRs more porous than at Apollo sites?
- If so, how porous and how thick is that porous layer?
- Are there other properties specific to PSRs that may affect trafficabilty?

In advance, I thank all the participants in today's workshop.

Additional Information

A briefing with additional details about lunar soil properties is posted at

http://www.lpi.usra.edu/science/kring/lunar_exploration/briefings/lunar_soil_physical_properties.pdf

A series of documents about lunar rovers and trafficability are posted at

http://www.lpi.usra.edu/lunar/documents/index.shtml#rovers

References

W. D. Carrier III, G. R. Olhoeft, and W. Mendell (1991) Physical Properties of the Lunar Surface. In *Lunar Sourcebook: A User's Guide to the Moon*, G. Heiken, D. Vaniman, and B.M. French (eds.), pp. 475-594, Cambridge University Press, Cambridge UK.

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M. Lemelin, D. M. Blair, C. E. Roberts, K. D. Runyon, D. Nowka, and D. A. Kring (2014) High-priority lunar landing sites for in situ and sample return studies of polar volatiles. *Planetary and Space Science 101*, 149-161.